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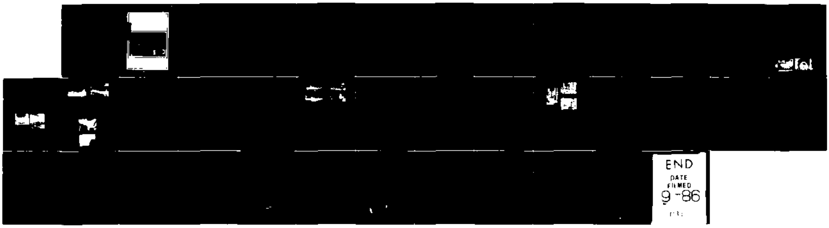

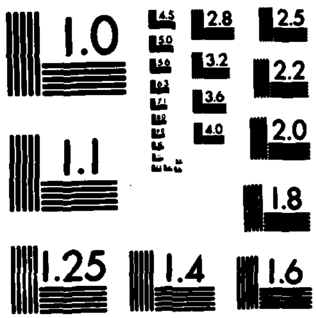

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Crashworthiness of Airframes

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Report No.737

CRASHWORTHINESS OF AIRFRAMES

Papers presented at the 61st Meeting of the Structures and Materials Panel of AGARD
in Oberammergau, Germany, 8—13 September 1985.

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Published April 1986

ISBN 92-835-1525-0

SPS

Printed by Specialised Printing Services Limited
40 Chigwell Lane, Loughton, Essex IG10 3TZ

CONTENTS

CRASHWORTHINESS - ANALYTICAL PREDICTIONS

by
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(Originally presented at the 61st Meeting of the Structures and Materials Panel,
September, 1985)

SUMMARY

A brief overview is given of the past and future development of analytical methods for predicting the crashworthiness of aircraft and components. The conclusions are that current numerical finite-element programs are becoming useful design tools, but that future component models may still need experimental derivation, particularly if made of fibre-reinforced composites.

1. INTRODUCTION

Crashworthiness is taken to mean the ability of fixed wing aircraft and helicopters to survive low-velocity impacts so that the airframe surrounding crew and passengers does not deform to produce direct injury, nor will the seats and attachments impart unacceptable decelerations to the occupants. Further consequences such as release and ignition of fuel, containment of fire hazards and avoidance of toxic fumes are important, but are not considered here. Crashworthiness is recognised as important; and legislation exists for automobiles and rail transport in many countries. It is considered important for all civil aircraft and helicopters, and for military transport aircraft, helicopters and naval aircraft, but not apparently for high performance military aircraft. The low-velocity survivable crash is most likely in helicopters and this increased risk is matched by the rewards of good crashworthiness since expensive crew are vulnerable to the vertical descent of a heavy engine, gearbox and rotor assembly. This has been recognised by the effort put into the U.S. Army Crashworthiness Programme [7,8]. Crash cases of fixed wing transport and civil aircraft are not uncommon, and the fuselage and subfloor should be crashworthy. Full-scale drop tests have been performed on such aircraft [18] at sink speeds of 17 ft/sec.

It is self-evident that realistic analytical predictions are preferred to full tests [1,2,3,17] in the design and evaluation stage. The recent full-scale Boeing B-720 test conducted by NASA/FAA was the culmination of a long preparatory programme [5]. The other alternative is a scale model analysis which has been used for both composite and metal structures, but it is recognised now that scaling effects at high strain rates are not understood well enough to lend confidence to model simulation [4]. It is timely therefore to view the progress and potential in analytical methods.

2. QUASI-STATIC ANALYSIS

Structural resistance to rapid deceleration has been posed as a quasi-static problem where maximum expected decelerations are simply specified, based on past evidence for various aircraft types and forced landings or survivable crashes. Thus seats and attachments in civil aircraft are subject to an inertia loading or impulse acceleration. Similarly fuel forward-inertia loadings are applied to ribs in swept wing boxes. The assumed decelerations can be improved upon by treating the aircraft as a rigid body and solving the equations of motion from assumed pre-crash conditions. As the interaction between the ground and structure is not tractable in this case, some empiricism is necessary. Correlation between simplifying assumptions and full-scale tests by NASA [9] shows that impulse-momentum arguments work reasonably well if a triangular impulse is assumed. The deceleration phase after a crashed landing can be prediced using an equivalent coefficient of friction. The deduced translational and rotational decelerations can be used for stressing seats etc. and for limiting body forces.

However, it is recognised that quasi-static loading will err on the low side if the rise time of the loading is comparable with the fundamental quarter period of the deforming structure. The time of impact, during which deformations of passenger/crew cabins are severe, may be only a fraction of a second, but this can be matched by the periods of very local deforming modes of the impacted structure. It is necessary therefore to include structural deformation and construct numerically the dynamic progress and energy absorption. Several commercial programs will do this numerically for general situations.

3. ANALYSIS OF STRUCTURAL IMPACT

Early research in the fifties and sixties into the use of numerical methods for impact studies owes much to Wilkins [6] at Lawrence Livermore National Laboratories from which stemmed the finite difference code HEMP; and PISCES and DYNA 3-D from the same

stable, and very much in use to-day. Developments of HEMP at E.S.I. have been used successfully for astronautical problems [10]. These explicit codes are designed for three-dimensional stress-wave problems in solids and fluids, and are most appropriate for high speed balistics, shock, cavitations, and the many phases involved in hyper-velocity impact. These codes can be quite horrendously expensive in computing time due to the small time steps and general nature of the field problem. If we confine the problem to the moderate velocities of survivable crashes, and further recognise that aircraft structures are assemblies of thin beams, plates and shells, then alternative special-purpose finite-element codes, using up-dated Lagrange descriptions, are more appropriate and very much cheaper to run.

Much development work has been reported for impact studies, centering on the time integration algorithms, the constitutive material laws, and the cheapest finite element that can safely model large elastoplastic deformations. It was originally assumed that explicit codes were potentially the best since they coped easily with nonlinearities, small incremental plasticity and displacement, kinematic hardening, etc. and the small time steps necessary were no hardship since impact durations were small anyway. Implicit codes like Newmark Beta can be used unconditionally with large time steps but are demanding on CPU time. The pros and cons are not yet resolved, and most codes contain options. The choice depends on the necessary degrees of freedom, the degree of non-linearity, and the available hardaware. Nonlinear iteration procedures used to saturate computers as large as the IBM 370 or CDC 760. They are less of a problem with the CRAY.1S or Cyber 205; and a bolt-on array processor could make the computing much less costly than the time taken to construct the finite element model.

A number of programs are available [10,11,12] to the aircraft industry of which KRASH [11] and DYCAST [12] are probably the most used in the U.S.A. (There is no analytical simulation in the U.K. Aerospace sector, although much activity in the car, train and nuclear sector.)

KRASH is not strictly a finite element program, since it idealises all structures as a series of light beams connecting rigid lumped masses. It recognises that large-deflection elasto-plastic behaviour is grossly nonlinear but, because of the highly idealised structure is able to pose the nonlinearities in terms of simple beam deflections and large rotations. The nonlinear stiffness behaviour of component beams are frequently found directly by experimental test. Wittlin refers to this as a "hybrid model" and another AGARD report [19] contains many examples of the use of KRASH as part of a joint FAA/NASA program.

A true finite element approach is that used in DYCAST which can be found in the accounts of the work by NASA [13] and Grumman [14]. DYCAST evolved from the NASA non-linear program PLANS, and can use explicit or implicit forms. All the programs have to cope with large deformations and elasto-plastic behaviour in thin plates and beams, since this is where the initial energy absorption takes place, and is the usual mechanism by which maximum deceleration can be limited at (hopefully) a constant value. Another vital feature is the capability of handling 'bounce' using gap elements for instance, and for imposing contact or sliding boundary conditions. The material properties should go further than traditional yielding and embrace kinematic hardening, otherwise a nominal maximum strain-to-failure has to be imposed. Good graphic displays of deformations are crucial since these time-marching programs can deliver prodigious amounts of data for the analyst. Adaptive time steps are necessary so that iteration and stability can be controlled during the course of the program to match the current state of the deforming structure.

4. MODELLING

It is well-known that dynamics is more expensive than static analysis, and some reduction or condensation is not only necessary but realistic, since minute detail and very high frequency modal response is absent in any real problem of vibrations. This is not however true in deformable crash dynamics where high frequency response and local deformation is the norm. This virtually excludes a finite element model of the whole aircraft structure ready to be impacted at any point. Some simplified modelling has to be undertaken.

Studies have been made on structural components, such as:-

(a) Seats with energy absorbers [13]
(b) Crushable floors in helicopters, made of composites having energy absorbing tubes infilled with foam [14]
(c) Helicopter crushable floor having stiffened ribs [10]

These studies show that the interaction between inertia forces and elasto-plastic development leads to behaviour and failure not expected in a static analysis. The development of the energy-absorbing mechanism can be extremely sensitive to the initial large deformations such as section distortion, shell folding, rivet popping and so on. Thus to properly describe the behaviour of stiffened plates, sandwich panels, or any mechanical or bonded joints, would require such a fine finite element mesh that the consequent minute time steps would make a global solution of the crashing vehicle impossible.

The usual solution is to replace the deforming component or substructure with a single nonlinear superelement whose properties are found by experiment or by a separate refined finite element analysis [10,13]. Some experience is still needed to do this. The experimental test will give an equivalent nonlinear stiffness but the static mode shape may differ considerably from the mode excited at impact. But the refined finite element model also has to be simplified so that any important coupling in the reduced degree-of-freedom can be reproduced at the interface of the superelement. Experimentally derived properties seem to have been favoured so far, but the experience gained, combined with the emergence of smart graphics and cheaper computing power will see an increase in finite element derived superelements.

5. COMPOSITES

If analytical models have proved difficult to construct for metals, there needs to be much more experience shared for composite behaviour in crash situations. Simple elasto-plastic models are no longer useful, and the energy release process in composites is a complex combination of fibre fracture and pull-out, debonding, and matrix cracking or crushing. It seems inevitable that experimentally deduced properties have to be used. Yet here there is conflicting evidence. It used to be assumed that deformation of carbon composites was largely elastic but impact work on chamferred tubes [15] shows that energy absorption can be far superior to conventional metal tubes. Recent work [16] at DFVLR on composite stiffened beams, for crushable aircraft subfloors, has shown that spars with sine-wave web (AV-8B or Jaguar demonstrator) absorb more energy per mass than stiffened light alloy plates or sandwich honeycomb.

Clearly more experience needs to be shared in composite components designed to absorb energy, and this includes complete fuselage sections as well as subfloors, seats and attachments, and undercarriage assemblies. There has been much work on minimising damage mechanisms due to high velocity small impacters, with the aim of preserving residual strength. Perhaps the time has come to turn to ways of maximising damage mechanisms to absorb energy.

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Transport Aircraft Structural Crash Dynamics Analysis and Test

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ABSTRACT

Recent accomplishments in Transport Category Aircraft Structural Crashworthiness research is presented in this paper. The application of computer program KRASH to transport category aircraft structure to evaluate crash dynamic response behavior is discussed. A brief description of the current KRASH85 version, along with an identification of experimental verification, is included. Analysis results, using KRASH, are compared with section drop test data. A drop test of a complete narrow-body airplane is described, along with the manner in which results from this test are used in subsequent full-scale crash test analysis. Pre- and post-test results of a controlled impact demonstration (CID) test, along with test results, are presented. Recently performed tests in which comparative specific energy absorption data for metal and composite structure for use in a transport category airplane are described. A description of future related planned activities is presented.

INTRODUCTION

During the 1970s, the application of computer technology to analyze large nonlinear behavior of rotary and fixed-wing aircraft structure improved significantly. A number of full-scale section and airplane impact tests were performed and the results were correlated with the analyses. During this period, the idea of approximating the nonlinear behavior of large regions of structure with simplified representations, supported by test data, showed great promise. This approach is often referred to as "hybrid modeling." Digital computer program KRASH, in particular, has been used extensively throughout the aircraft industry. Program KRASH was initially used to model helicopters (Reference 1) subjected to multidirectional forces. Subsequently, the application of the program was extended to light fixed-wing aircraft (Reference 2) and currently it is being used to model large transport aircraft (Reference 3).

Modeling of aircraft structure for crash impact conditions, which invariably result in large deformations, has been shown to be enhanced with the use of computer programs such as KRASH which use empirically developed data. This approach becomes more significant as aircraft structures increase in size and complexity and as advanced materials are used more extensively. This paper describes recent accomplishments in testing and analysis of transport aircraft size structure, including designs of metal and composites. As part of a joint FAA/NASA program (Reference 4), airframe section drop tests, full-scale airplane drop tests, and a controlled impact demonstration (CID) tests, were performed to provide data to evaluate crash floor pulses and validate analytical programs such as KRASH. Included in this paper are recent results of analytical modeling versus test data for airframe section and full-scale airplane impact tests.

Future designs of transport aircraft could incorporate composite materials in impact-critical regions. To ascertain the feasibility of designing fuselage structure for crash loads, a study was initiated which involves testing and analysis of structural elements (Reference 15). Comparative data from some of these tests involving both metals and composites are also provided.

PROGRAM KRASH DESCRIPTION AND VALIDATION

Program KRASH is a hybrid digital computer program that solves the coupled Euler equations of motion for N interconnected lumped masses, each with a maximum of six degrees of freedom defined by inertial coordinates x_i, y_i, z_i and Eulerian angles ϕ_i, θ_i, ψ_i, $i = 1, \ldots, N$. A hybrid model allows the user the flexibility of using available information, experimental or analytical, in the development of the structural representation. The interaction between the lumped masses is through interconnecting structural elements (beams) which are appropriately attached (pinned, clamped). These interconnecting elements represent the stiffness characteristics of the structure between the masses. The beam elements have both linear and nonlinear (post-yielding) characteristics, defined by user input data. The equations of motion are explicitly integrated (Euler predictor-corrector scheme) to obtain the velocities, displacements, and rotations of the lumped masses under the influence of external forces (such as gravity, aerodynamic and impact forces), as well as internal forces. Use of the incremental deflections which occur during each time step leads to a set of incremental forces calculated using a linear stiffness matrix and nonlinear stiffness reduction factors from the user input.

Program KRASH has had extensive experimental verification. A summary of aircraft configurations and conditions, which demonstrates the extent of KRASH correlation with experimental data, is shown in Table 1. With the exception of the one test with a transport airplane, all the experimental data were obtained primarily with validation of analytical modeling in mind.

TABLE 1. KRASH EXPERIMENTAL VERIFICATION

TEST NO.	AIRCRAFT	GROSS WEIGHT (LBS)	IMPACT VELOCITIES (FPS) VERTICAL	LONGITUDINAL	LATERAL	(REFERENCE)
1.	ROTARY WING, UTILITY TYPE	6600	23	–	18.5	(1)
2.	SINGLE-ENGINE, HIGH-WING	2400	46	70	–	(2)
3.	SINGLE-ENGINE, HIGH-WING	2400	22	71.3	–	(2)
4.	SINGLE-ENGINE, HIGH-WING	2400	49	70	–	(2)
5.	SINGLE-ENGINE, HIGH-WING*	2400	43	69.5	–	(2)
6.	TWIN-ENGINE, LOW-WING SUBSTRUCTURE	545	27.5	–	–	(16)
7.	ROTARY-WING CARGO TYPE	24300	42	27.1	–	(17)
8.	ROTARY-WING MULTI-PURPOSE	3800	19.7	19.7	–	(18)
9.	ROTARY-WING MULTI-PURPOSE	3620	32.8	–	–	(18)
10.	ROTARY-WING COMPOSITE SUBSTRUCTURE	3530	30.0	–	–	(19)
11.	ROTARY-WING COMPOSITE SUBSTRUCTURE	3530	28.2	–	10.3	(19)
12	MEDIUM SIZE TRANSPORT*	159000	18	172	–	(3) (10)
13.	MEDIUM SIZE TRANSPORT	192000	17.3	255	–	(11)**

*TEST PERFORMED ON SOIL; ALL OTHER TESTS ON RIGID SURFACE.
**TO BE PUBLISHED

The current version, KRASH85 (Reference 5), contains among its many features the ability to:

- Represent general, nonlinear stiffness properties in the plastic regime, including different types of load-limiting devices, and a plastic hinge moment algorithm.
- Define occupiable volume infringement due to structural deformation and output a measure of occupant injury potential (Dynamic Response Index).
- Simulate contact between structure and a generalized impact surface, including sliding friction, and the treatment of the impact surface as rigid or flexible.
- Calculate aircraft, or airframe section center-of-gravity acceleration, velocity, and displacement; and the energy distributions among the masses, elements, and external springs (kinetic, potential, strain, damping, crushing, and friction).
- Permit general initial conditions of linear and angular velocity. Initial condition balance is NASTRAN-MSC coupled.
- Model shock struts, including a gear-oleo element metering pin.
- Apply acceleration, external force excitations and aerodynamic forces.
- Use Load Interaction Curves (LIC) to assess combined load failure.

APPLICATION TO TRANSPORT AIRCRAFT STRUCTURE

Methodology

The FAA and NASA jointly, with the assistance of industry, embarked upon a program to develop a technical database and methodologies necessary to assess the dynamic impact environment and requirements needed for occupant survivability in survivable accidents involving civil aircraft. This long-range program started in the late 1970s. A review of the FAA/NASA/Industry effort, which is shown in Figure 1, was recently presented at a conference and workshop on cabin safety (Reference 6). Included in the joint FAA/NASA impact dynamics program was a review of the transport accident database (Reference 7, 8, 9), the formulation of candidate crash scenarios and the application of current methodology to transport airplanes. One of the first attempts to model transport behavior, using the current technology, is described in Reference 3. An L-1649 airplane impact onto an earthen mound was simulated using program KRASH. The test was performed nearly two decades earlier and is described in Reference 10. A sampling of the comparison of the analysis with test results is shown in Figure 2. Subsequent to this analysis, computer coding was modified to improve future modeling for additional crash scenarios.

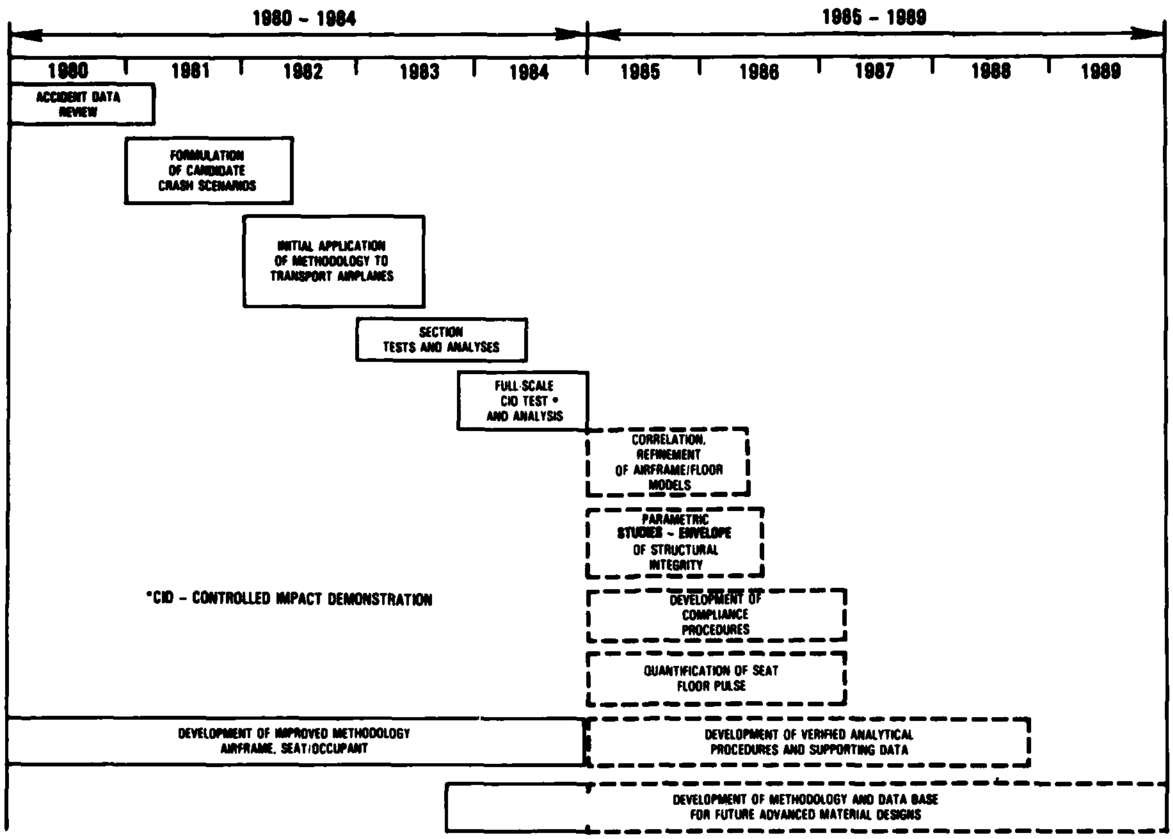
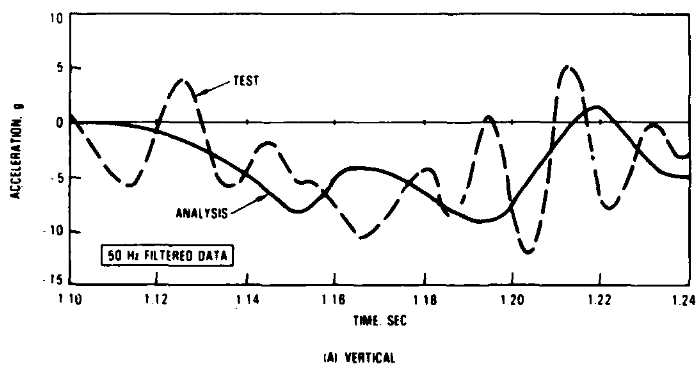


Figure 1. Transport Aircraft Impact Dynamics Program



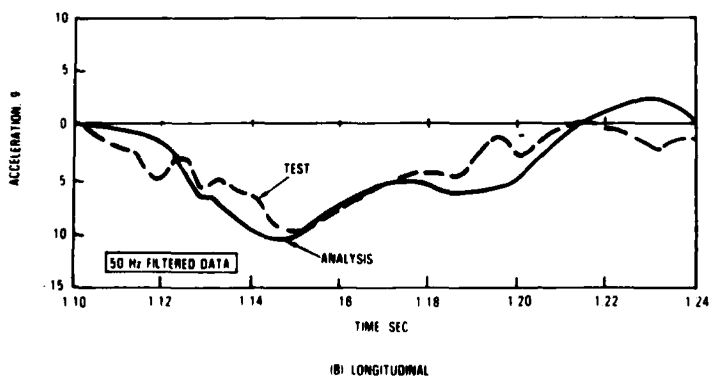


Figure 2. Comparison of Analysis and Test Measured L1649 Floor Pulse at a Mid-Fuselage Location

The methodology approach for crash structural dynamics analysis of transport aircraft which is described in Reference 11 consists of the use of the following:

- o Analytical models of airframe sections to generate load-deflection (crush) curves of the fuselage underside.
- o Supporting data from section and full-scale airplane drop tests to refine analytical representations of structure.
- o Analyses of various impact conditions (velocity, attitude) to determine loads and passenger floor acceleration pulses. The results of the analyses are then compared to the estimate of airframe capability to determine critical failure regions.

The development of an envelope of impact condition, acceleration response, and airframe structural capability is the goal of this approach.

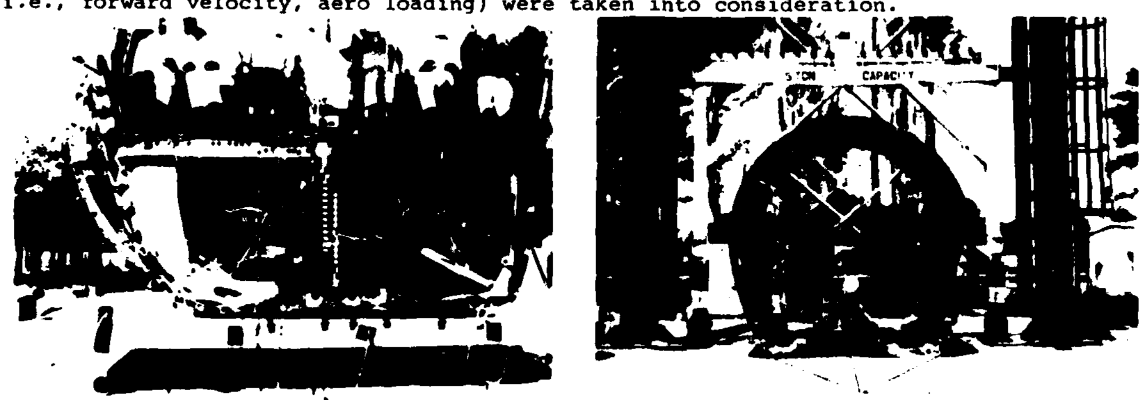
AIRFRAME SECTION TESTS

As part of an overall FAA/NASA joint effort to develop improved methodology, a full-scale test CID was performed. There were two test objectives: the primary objective of the test, from an impact dynamics perspective, was to acquire crash impact data and validate analytical models; the objective associated with anti-misting kerosene (AMK) experiments is not pertinent to this paper. In preparation for this test, the FAA conducted several airframe section drop tests as well as a full-scale drop test. The purpose of the supporting tests was to obtain fuselage crush data, hard point load-deflection, failure modes, and floor responses to compare with analytical models and improve the input data to perform structural response analysis for the CID test. The pre-CID test analysis is presented in Reference 11.

Figure 3 shows the post-test view of two narrow-body airplane frame section tests, with and without subfloor cargo loading. These tests are reported in References 12 and 13. The comparison of analysis and test results is shown in Figure 4. A wide-body airplane frame section was also drop-tested (Reference 14) at the FAA Technical Center, the post impact views of which are shown in Figure 5. A comparison between analysis and test results is shown in Figure 6. The test and analysis results from the wide-body fuselage structure are currently being used in a Transport fuselage composite technology study (Reference 15).

AIRPLANE DROP TEST

The FAA has also conducted a full-scale impact test of a narrow-body airplane (120 inches longer) of similar design to the CID test article. The impact conditions for this drop test were 17 ft/sec sink speed, +1 degree nose-up attitude, 195,000 pounds gross weight (the same as for the planned CID test, except for aerodynamic loading and forward velocity). The test was conducted at Laurenburg N.C. in July 1984. The primary purpose of this drop test was to assess potential structural damage, obtain crush characteristics along the fuselage underside for both hard (bulkheads) and soft (frames) structure and provide updated input to the analytical model. The pre- and post-impact views for this test are shown in Figures 7 and 8. A comparison of test and analysis results is shown in Table 2. The test provided results with regard to structural damage, crush characteristics, and failure modes for a known impact condition. For example, it was observed that hard points previously thought to have minimal crush distance, could in fact, crush several inches prior to restiffening. The crushed ducting, in the wing center section (Figure 9) illustrates this point. The bulkhead web failure, leading to floor disruption (Figure 10) provided an opportunity to reevaluate preliminary analysis model results. For example, the pre-CID analysis results were revised as a result of changes in load-deflection curves associated with the lower fuselage crush. Figure 11 illustrates the estimated response range before and after the "Laurenburg" test. The results of this test indicated that the planned CID impact condition would produce the desireable severe but survivable impact scenario. Differences between this drop test and the CID test (i.e., forward velocity, aero loading) were taken into consideration.



CARGO LOADING NO CARGO LOADING

Figure 3. Post-Test Views – Narrow-Body Airplane Fuselage Section Tests

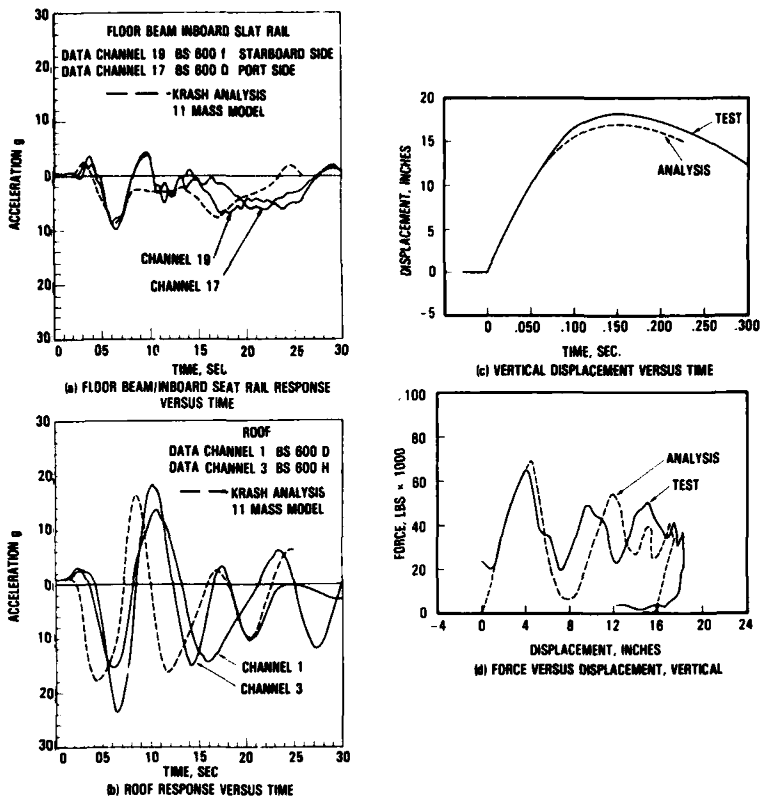
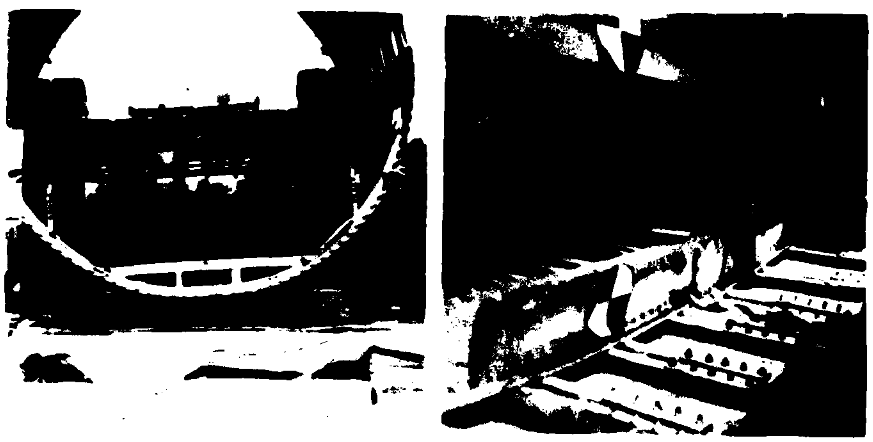


Figure 4. Comparison of Narrow-Body Fuselage Section Analysis and Test Results



OVERALL STRUCTURAL DEFORMATION

BUCKLING OF VERTICAL SUPPORT MEMBER

Figure 5. Post-Test — Wide-Body Airplane Fuselage Section Test

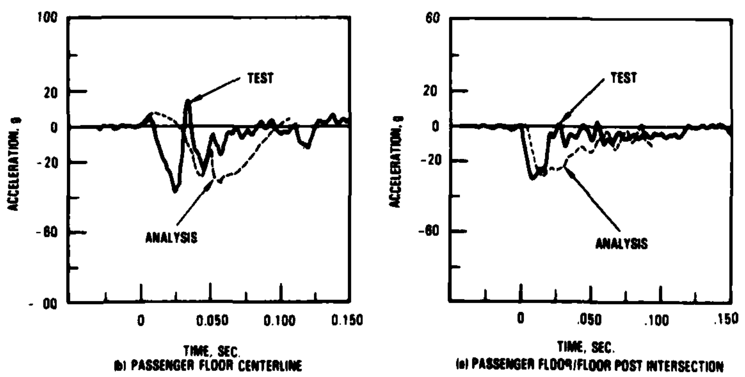


Figure 6. Comparison of Wide-Body Fuselage Section Analysis and Test Results

Figure 7. Pre-Test Setup — B-707 Impact Test

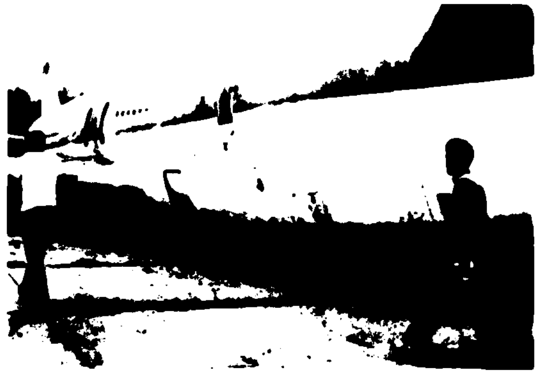


Figure 8. Post-Test View — B-707 Laurinburg Impact Test

TABLE 2. QUALITATIVE COMPARISON OF KRASH STICK MODEL AND FULL AIRPLANE IMPACT TEST

KRASH ANALYSIS RESULTS	TEST RESULTS
1. HIGH SHEAR LOADS IN FS 820-960 REGION	KEEL DAMAGE FS 820-960, BULKHEAD DAMAGE AT FS 820 AND 960.
2. NO SIGNIFICANT BENDING MOMENT AS EVIDENCED BY LOW INTERACTION CURVE LEVELS, PARTICULARLY IN AFT FUSELAGE	CARGO FLOOR DAMAGE SHOWS EVIDENCE OF CRUSHING IN LOWER REGION AND FRAME FAILURES.
3. SEVERE CRUSHING OF FUSELAGE AFT OF MLG BUKHEAD FS 960 12 INCHES. 5 TO 6 INCHES CRUSH FORWARD OF WING LEADING EDGE	DAMAGE AFT OF FS 960 MUCH MORE EXTENSIVE THAN FWD OF FS 620.
4. APPROXIMATELY 6 TO 9 INCHES OF CRUSH IN CENTER-WING SECTION	6" DUCTING IN CENTER-WING REGION SHOWS EVIDENCE OF COMPLETE CRUSH
5. SHOWS ENGINE CRUSHING ACCOUNTS FOR APPROXIMATELY 4% OF THE TOTAL ENERGY.	WHILE THE INBOARD ENGINE FAILS AT ITS UPPER ATTACH POINTS IT REMAINS LODGED BETWEEN WING AND GROUND.

Figure 9. Lower Wing Box and Keel Left-Hand Side View Shows Crushed Ducting

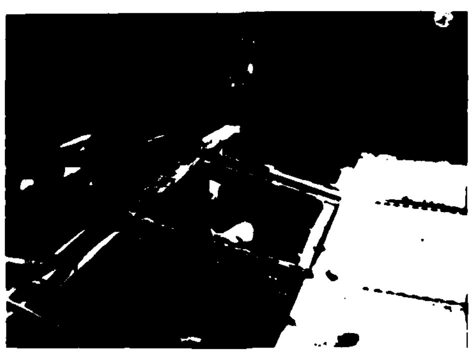


Figure 10. Looking at Left-Hand Side of FS820 Bulkhead

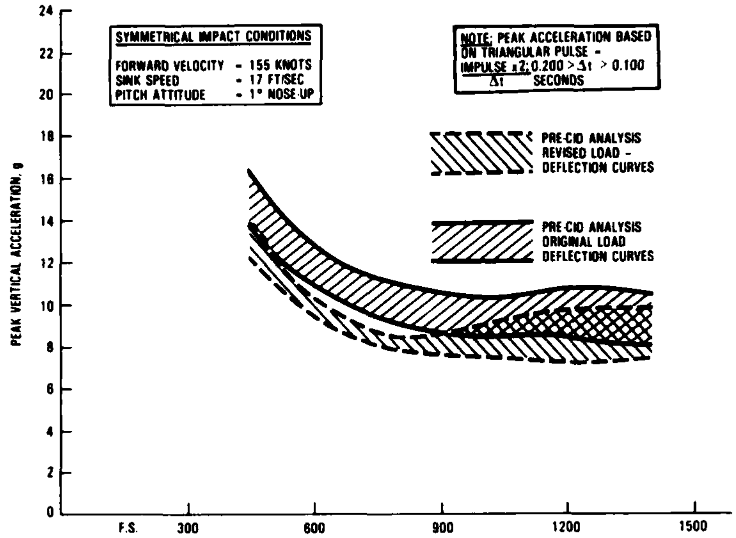


Figure 11. Comparison of Pre-CID KRASH Stick Model Analysis Results — for Planned Symmetrical Impact Condition — Original vs. Revised Load Deflection Curves

CONTROLLED IMPACT DEMONSTRATION

The planned impact scenario for the CID test is shown in Figure 12. Two KRASH models developed for the CID test are shown in Figures 13 and 14. The 17-mass, 16-beam element stick model, Figure 13, provides overall airframe response and is useful in assessing airframe structural integrity and floor accelerations, particularly in impacts where the airframe low-frequency responses are expected to predominate. An expanded CID model (48 masses, 137 beams) shown in Figure 14 may be more beneficial in assessing detail response, provided proper representation can be achieved. Pretest analysis results indicated the following:

- o Crush distances of approximately 4 to 6 inches along the forward fuselage underside, 5 to 10 inches in mid fuselage and 10 to 14 inches in the aft fuselage.

- o The load interaction curve (LIC) ratio, which compares shear-moment forces with estimated airframe capability, showed potential for experiencing loads near the estimated fuselage strength in the region of FS960-1040 (main landing gear bulkhead).

- o Floor triangular pulse-shaped peak vertical accelerations between 8g and 10g in the passenger region (FS 460-1200). Peak longitudinal accelerations approximately 4g along the fuselage. Figure 15 shows the pretest analysis results for floor responses.

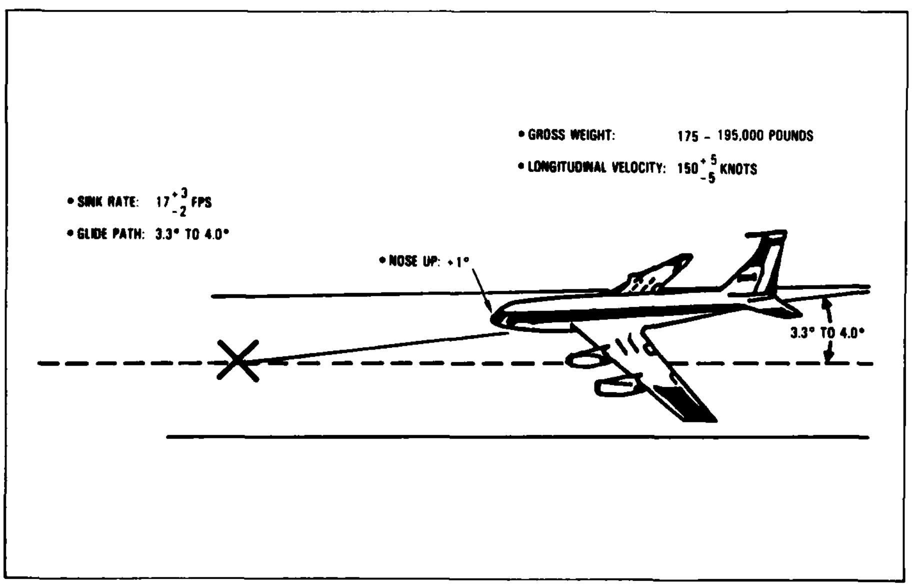


Figure 12. Planned CID Impact Scenario

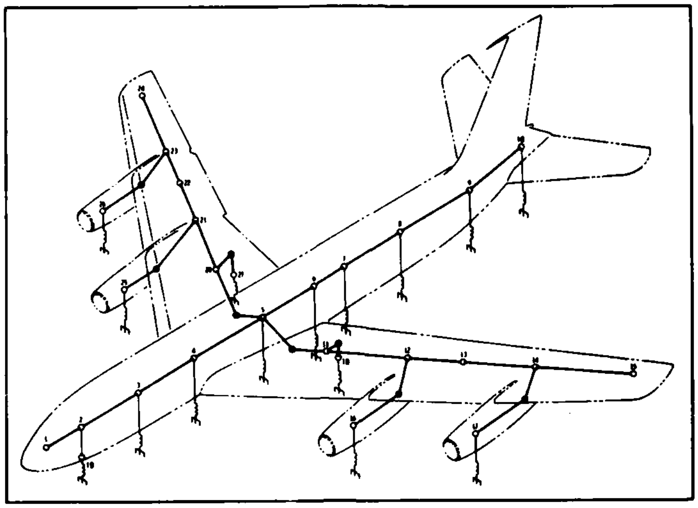


Figure 13. CID Stick Model (Reference 3)

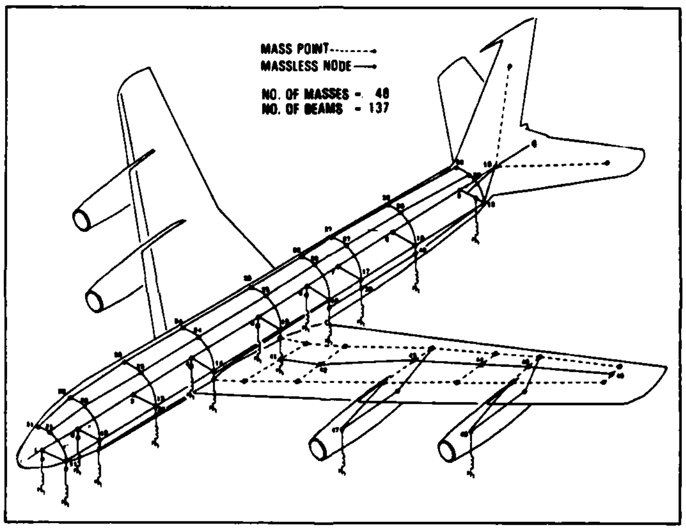


Figure 14. Expanded CID Model (Reference 3)

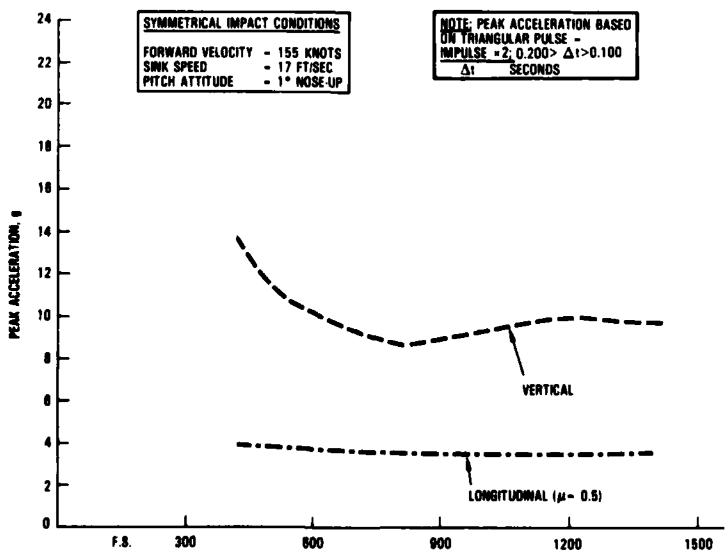


Figure 15. Pre-CID KRASH Stick Model Accelerations for Planned Symmetrical Impact Condition

The stick model, due to its coarseness, tends to provide lower frequency acceleration responses than the expanded model. The higher peak accelerations are generally associated with shorter duration pulses than the lower peak values. Acceleration peak responses are plotted in Figure 16, along with a constant ΔV = 17 ft/sec. curve. The data cluster about the constant ΔV curve. The stick model results tend to be of a lower amplitude and broader in response duration. As the expanded model results are filtered to a lower cutoff value, the response shifts to a lower value and tends toward better agreement with the stick model and results. An alternative to comparing peak values is to present an equivalent triangular pulse amplitude which can be obtained from a plot of impulse (g-sec) data, which is the acceleration integrated over time for the period of interest. This provides an average value. The peak associated with a triangular pulse is twice the average value. This approach eliminates questions that could arise over the print interval or filter characteristics (i.e., cutoff frequency, decay rate). Figure 17 shows a comparison of the pretest analysis results for the stick and expanded models on the basis of equivalent triangular pulse peaks. An expanded model using equivalent triangular responses still shows higher accelerations through the passenger floor region but the differences are smaller than when comparing only peak values.

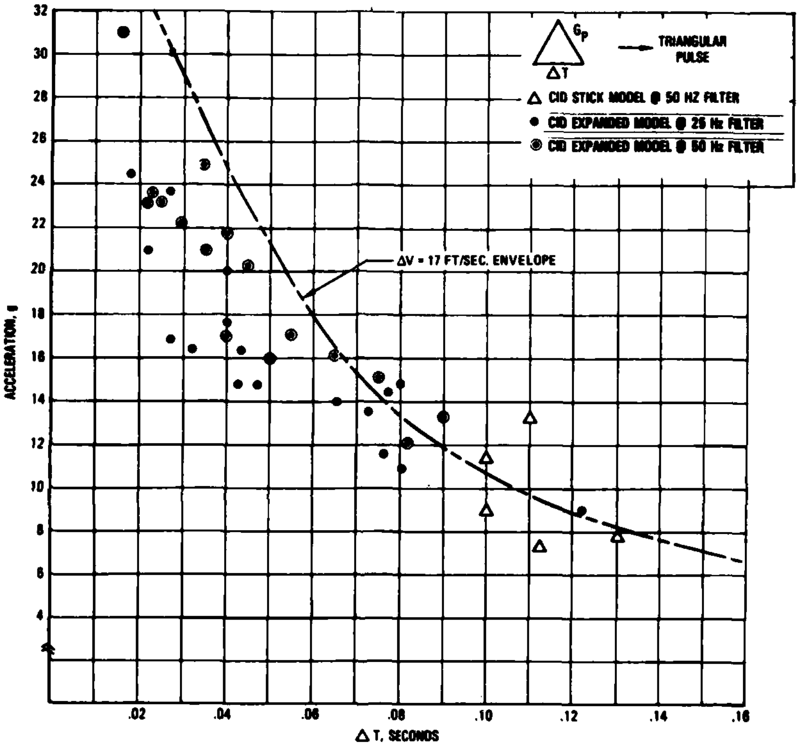


Figure 16. CID Pre-Test Analysis – Vertical Acceleration Pulses, 17 ft/sec, +1° Nose-Up

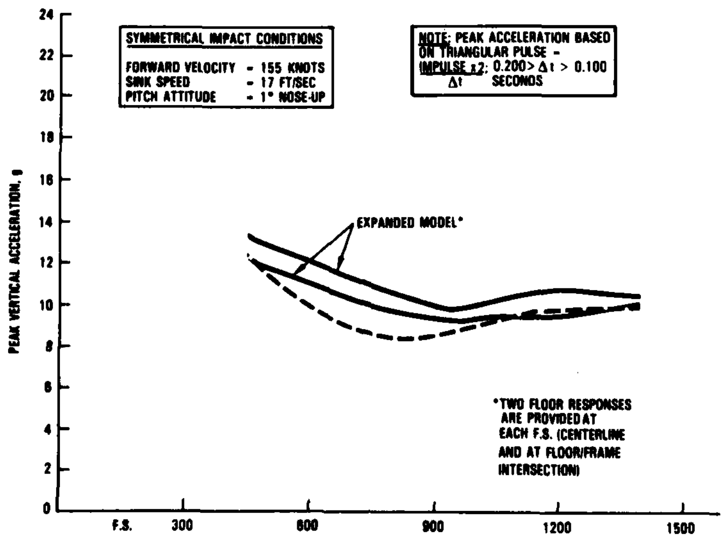


Figure 17. Comparison of Pre-CID KRASH Stick and Expanded Models Analyses Results for Planned Symmetrical Impact Condition

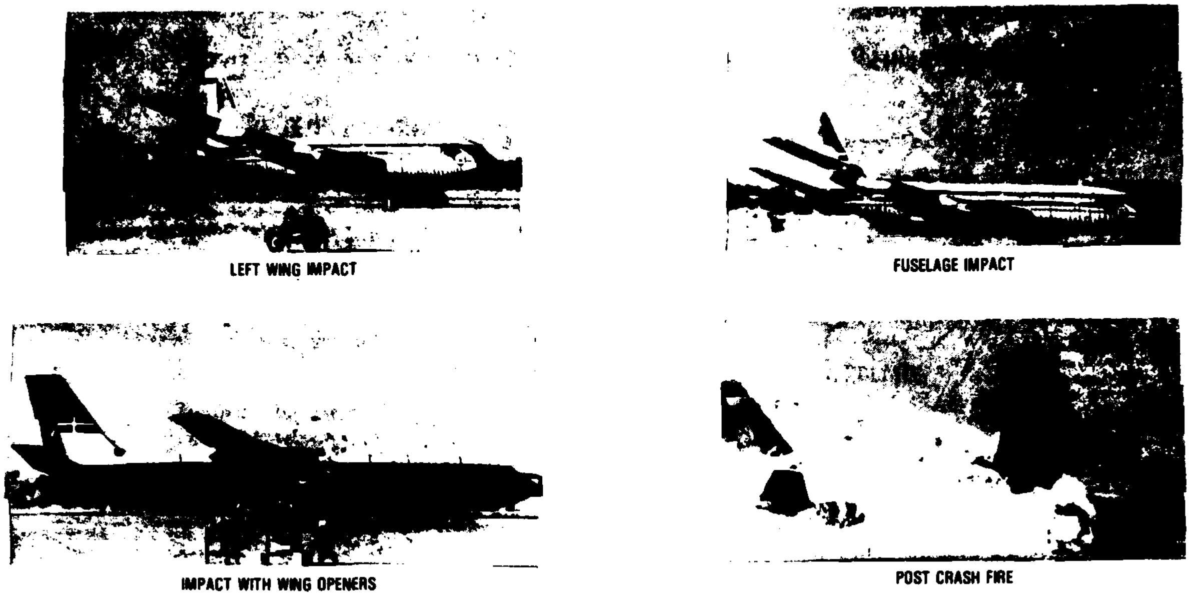


Figure 18. CID Impact Sequence

The CID test was performed on December 1, 1984, at the NASA Dryden Dry Lake Bed, Edwards Air Force Base, CA. The actual impact conditions deviated from the planned conditions as shown in Table 3. Due to an initial roll and yaw, the aircraft impacted on the left wing outboard engine (No. 1), rotated onto the No. 2 engine and then impacted the forward fuselage nearly 400 msec. after No. 1 engine contact. Peak ground impact responses were developed within 500 msec. after initial fuselage impact. The emphasis for the analysis is to determine floor responses so as to ascertain the potential effect on seat-testing requirements. The initial engine impacts with the ground have little bearing on the floor peak responses. Thus, as a first priority, the analysis was performed for the initial fuselage impact. For simplification, the impact was considered to be symmetrical. The magnitude of the lateral accelerations and differences between left and right side responses indicate that a symmetrical analysis will be a satisfactory first approximation. The analysis has simulated the test for more than 500 msec. after initial fuselage impact.

The actual CID impact sequence is shown in Figure 18 and includes wing cutter impact and subsequent initiation of postcrash fire. The post-test correlation consisted of: comparisons for measured fuselage bending responses, lower fuselage crushing and peak floor accelerations with the KRASH stick model results. Bending bridge data were measured at six fuselage stations (Forebody Stations BS410, BS510 and BS600J and Aftbody Stations BS1030, BS1130 and BS1250). The moment response data indicate that the fundamental frequency response mode is approximately 3. to 3.5 Hz and that structural damping is approximately 7 percent of critical. As part of the correlation effort, the KRASH stick model frequency and damping characteristics were determined and compared to those of the test article (as noted in the bending data). The response frequency for the KRASH model is approximately 3 Hz, and the structural damping is estimated to be approximately 8 percent of critical. Thus, the KRASH stick model contains stiffness, mass, and damping properties consistent with the test article. KRASH stick model analysis results for the actual CID fuselage impact condition versus measured test results are shown in Figures 19, 20 and 21 for accelerations, crush and moment distribution. The correlation between test and analysis was performed for the symmetrical impact onto the fuselage which incorporated the following initial conditions:

- 14 ft/sec sink speed
- 262 ft/sec. (~160 knots) longitudinal velocity (this parameter was not varied. A slight variation from actual test conditions is not significant).
- Pitch attitude -2 degrees (nose-down)
- Ground coefficient of friction (μ) = .5

The load-deflection characteristics of the fuselage underside were similar to those used in the pretest CID analysis. The longitudinal acceleration levels are relatively low and in agreement with the test results. (The correlation of the analysis with test results, showed some differences.) The aftbody down bending moments are higher than those measured. Using the LIC ratios, the post-test analysis results do not indicate that fuselage moments and shears will be high enough to cause airframe failure. The crushing of the fuselage from the MLG aft is probably more than experienced at impact; however, the more extensive aft fuselage crush occurs toward the end of the ground impact, while the aircraft is settling to final position and does not influence the peak responses. Of interest to note is that the pretest CID model (mass, stiffness, damping, crush characteristics), was not altered. The correlation effort concentrated on determining the

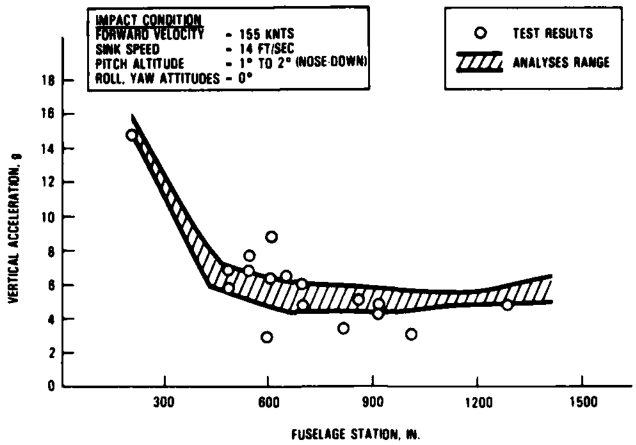


Figure 19. Comparison of Post-Test CID KRASH Analyses and Test Results for Fuselage Impact

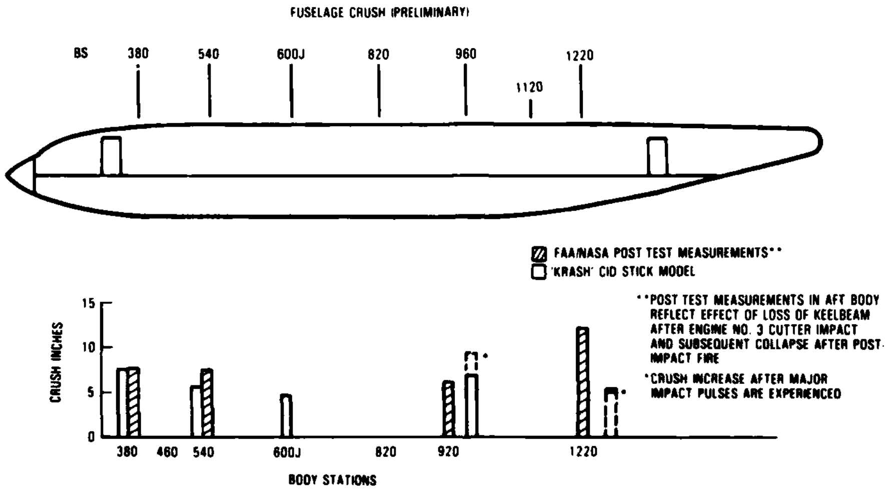


Figure 20. Comparison of Measured Pulses and KRASH CID Stick Model Results

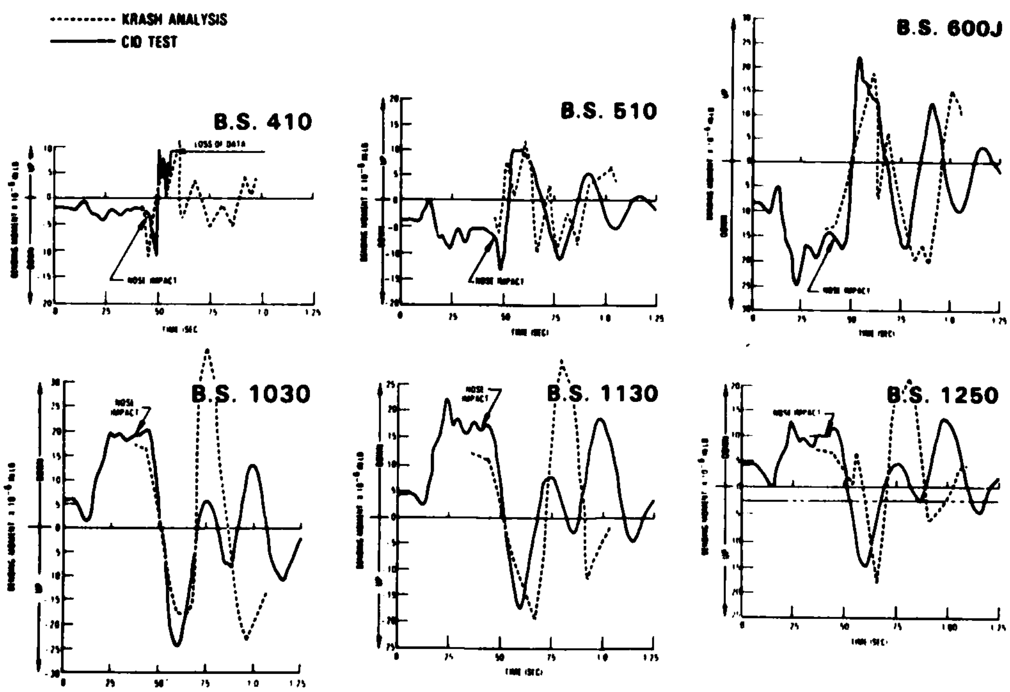


Figure 21. KRASH versus Test Results, 2-Degree Nose Down Attitude, 14 ft/sec Sink Speed for the CID Fuselage Impact are Compared

initial aerodynamic loading and impact attitude associated with the fuselage initial impact representative of the CID test. As part of the correlation effort a comparison between analysis and test will also be performed for the initial unsymmetrical impact or the No. 1 engine for the conditions noted in Table 3.

TABLE 3. COMPARISON OF CID TEST PLANNED AND ACTUAL IMPACT CONDITIONS

	PLANNED	ACTUAL*
SINK RATE, FPS	17^{+3}_{-2}	17.3
GROSS WEIGHT, LB	175 - 195000	192,383
GLIDE PATH, DEGREES	3.3 TO 4.0	3.5
ATTITUDE, DEGREES	1 ± 1 (NOSE-UP)	0
LONGITUDINAL VELOCITY, KNTS	150^{+5}_{-5}	151.5
ROLL, DEGREES	0 ± 1	-13
YAW, DEGREES	0 ± 1	-13

*IMPACTED ON LEFT WING OUTBOARD ENGINE. INITIAL CONTACT ON FUSELAGE WAS AT FOLLOWING CONDITIONS: 14 FT/SEC SINK SPEED, NOSE-DOWN ATTITUDE (0 - 2.0 DEGREES), FORWARD VELOCITY 150 KNTS, CONTACTED FUSELAGE (BS 360 - 460) REGION.

A difficulty in matching all the test results, other than the fact that a math model can only approximate complex nonlinear behavior, is that there are many variables that are not known. The modeling described is a symmetrical representation of an unsymmetrical impact. Initial conditions, such as rotational velocity, rotational acceleration, and time-varying external loading, along with the sequence and the magnitude of the fuselage underside crush influence the magnitude and phasing of the responses.

COMPOSITE FUSELAGE TECHNOLOGY

The primary crash dynamics technology problem associated with transport airplanes designed with advanced composite materials is to achieve energy absorption and load-carrying capability comparable to that of current metal designs. An attempt to advance transport fuselage composite technology with regard to impact dynamics is currently being performed (Reference 15). The approach being followed in this program is outlined in Figure 22. The fuselage structure that was fabricated, analyzed, and tested is representative of current wide-body aircraft structural elements which are located in the underside of the aft fuselage, as noted in Figure 23. The status of this effort is described in Reference 20. Analysis was first performed to quantify response characteristics of current baseline metal designs, including load response and energy absorption. Replacement structural elements (i.e., stiffened panels and frame segments) were designed to meet the same operational shear load and stiffness requirements as their metal counterparts. It was found that the use of composites to replace metal structure

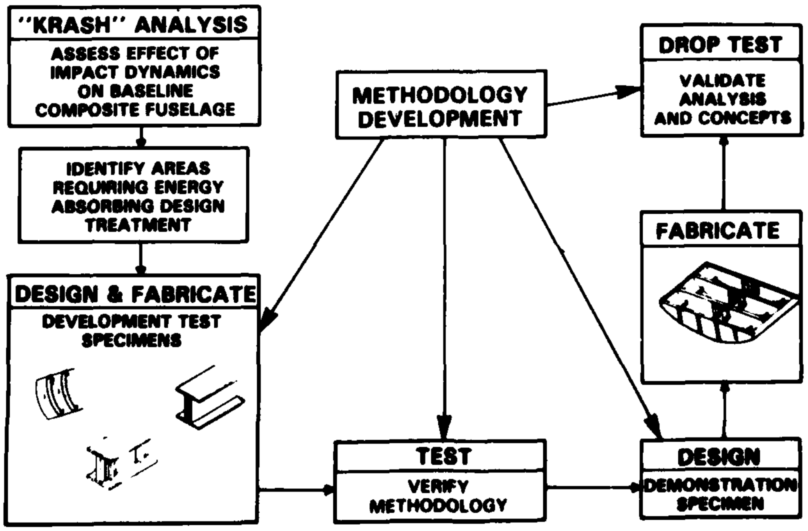


Figure 22. Impact Dynamics Approach

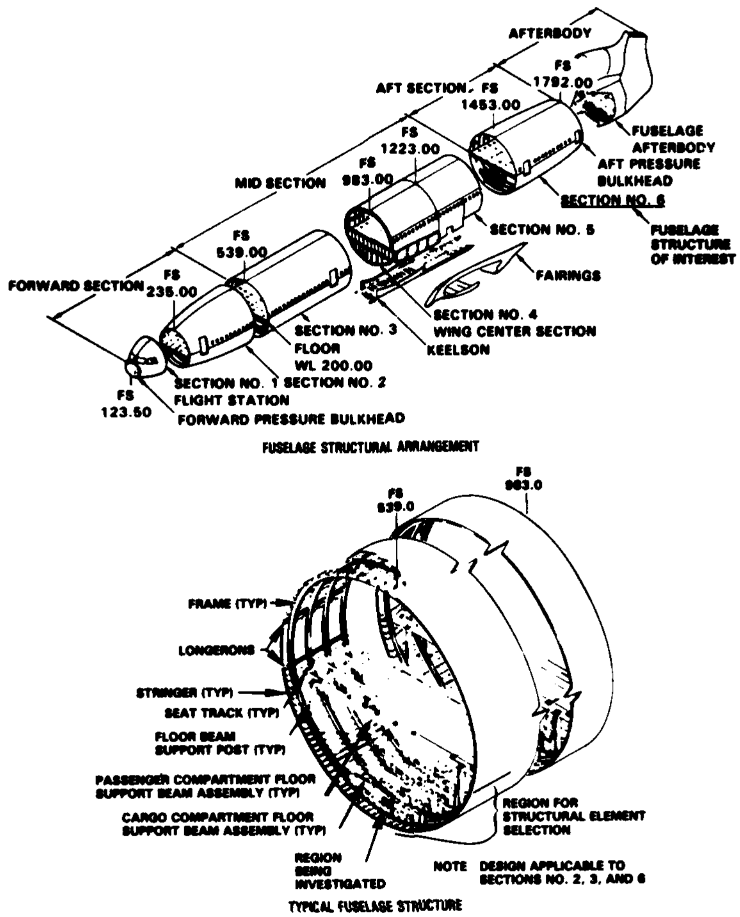
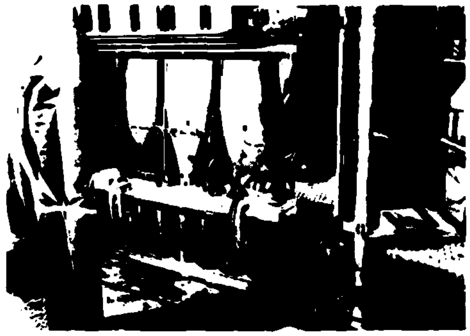


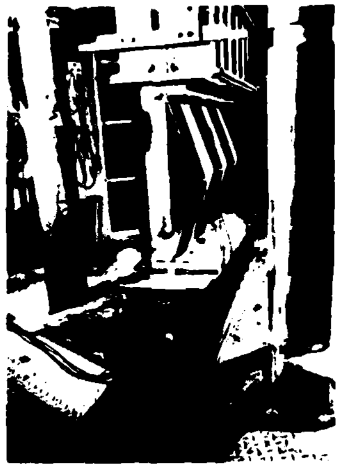
Figure 23. Transport Aircraft Composite Technology Structure for Impact Dynamics

can require different design concepts. For example, the metal-stiffened panels installed as they normally are in a wide-body aircraft, when loaded in compression, exhibited a different failure mode than either of two composite designs installed in the same manner, (Figure 24). The load- deflection, energy absorption and specific energy absorption comparisons are shown in Figure 25. The metal stiffened panel failed in bending, while the two composite elements exhibited material pull-out at the edge fasteners. Because of this failure mode, the stiffener had little influence on the outcome. While in this particular situation the composite design did not equal or better the metal design with regard to specific energy absorption one cannot generalize about composites versus metals. Compression loading of helicopter elements used in subfloor regions has shown comparable or better energy absorption than metals, provided attention is paid to detail considerations (i.e. load path, crush initiation). The effort described in Reference 20 is continuing with the emphasis on detail design. More importantly the data obtained on this program provides a quantification to just "how good" metals are, and more importantly, how much energy absorption comparable designs using composite materials must provide, as well as the relevance of failure modes. Thus, a databank for transport airframe crash design is evolving.

As noted in Figure 1, several research tasks are in progress. The post-CID test analysis is being performed to evaluate the initial unsymmetrical impact on the engines, as well as the merits of using an expanded model. Parametric studies are planned for the purpose of developing a crash design criteria envelope. Initially, these studies will be performed with the same aircraft design as that used in the CID test. Eventually, this effort will be expanded to include other aircraft configurations. The design of a composite fuselage for future application in transport aircraft is currently being studied (Reference 15). In this effort, baseline metal designed airframe component elements located in the lower fuselage have been designed, analyzed and tested to attain energy absorption data. Composite designs for replacement structure have similarly been designed, analyzed, and tested. Thus, not only has baseline metal performance data been obtained, but also a comparison of energy absorption and energy efficiency with composite design concepts is being evaluated. The preliminary results of this effort are described in Reference 20. The addition of dynamic testing of seats for use in transport aircraft category is also being evaluated. The results of much of the aforementioned tests and analysis will have a bearing on whether to perform dynamic tests for seats and if so, at what level. In addition, the development of a crash design envelope of airframe structural integrity versus impact condition for the purpose of assessing occupant survivability could have an influence on fuel containment design concepts. The latter is of concern for transport airplanes, and consistent design practice would indicate that selected crash scenarios should be applied to both trauma and fire related events, although some can be mutually exclusive.



COMPOSITE BLADE PANEL FAILURE



ALUMINUM PANEL FAILURE

COMPOSITE HAT PANEL FAILURE

Figure 24. Post-Test Views of Stiffened Panels Illustrate Different Failure Modes

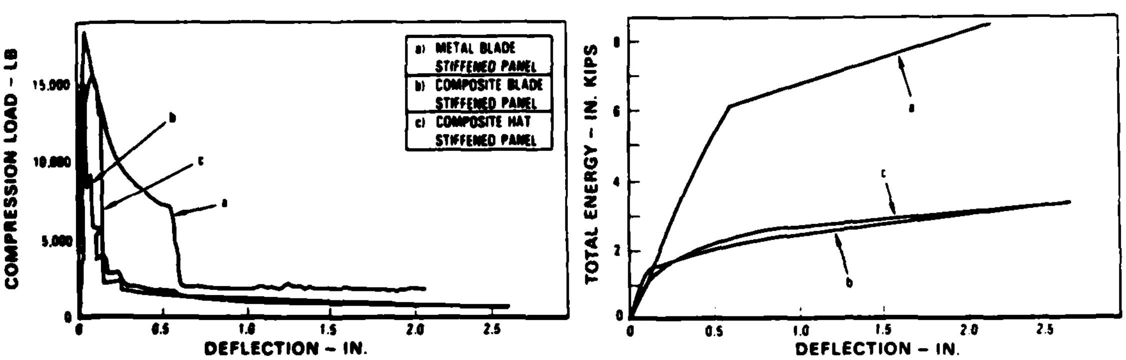


Figure 25. Comparisons of Load and Energy Absorbed versus Deflection for Stiffened Panels Under Compressive Static Loading are Shown

CONCLUSIONS

Methodology developed to improve Aircraft Structural Crashworthiness has shown much progress since the 1970s. The results of FAA/NASA sponsored research for impact dynamics of tranport category aircraft, involving the testing and analysis of large airframe sections and complete aircraft, has indicated the ability of analytical models to match test data and consequently be used to analyze designs for compliance with crash design criteria requirements. Program KRASH is currently being used by many rotary-wing and light fixed-wing manufacturers to evaluate aircraft crash design capability. Recently, the program has been expanded to apply to transport category aircraft. Preliminary comparisons of KRASH analysis with a recently completed full-scale CID test show good agreement. Additional effort to improve confidence in the methodology for a wide range of aircraft configurations and crash scenarios is in progress. Effort related to composite fuselage design for impact dynamic considerations has shown that the need to use design concepts in which crush initiation is controlled is needed in order to achieve energy absorption comparable to that of current metal designs. The technology development for transport aircraft structural crash dynamics analysis is an ongoing effort.

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CRASH SIMULATION MODELS AND INTERACTION WITH EXPERIMENTS

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SUMMARY

Crashworthiness studies require the use of analytical simulation models, since experiments alone are not sufficient nor adequate.

The paper outlines and discusses the main features that characterize analytical crash models, and their interaction with experiments. Some examples of crash models developed recently by different Institution and Companies in the world are then briefly reported and commented.

Finally some conclusions are drawn on future applications and trends; the use of complex analytical models will increase, while required experiments will decrease in quantity but increase in quality and in complexity.

1. INTRODUCTION

The obtainement of adequate structural crashworthiness is a very complex task, having several different facets, each of them requiring deep insight, and often interacting to eachother.

The different issues that must contribute to the development of a crashworthy design, summarized in figure 1, are at least the following:

a) definition of envelopes of potentially survivable crashes;

b) crash fire prevention;

c) design and verification of an inner structure providing a safe survivable space for the occupants, for all crashes within the envelopes defined by item "a";

d) design and verification of an outer structure capable of absorbing and dissipating energy with maximum efficiency, so reducing the accelerations at seat fixing points within reasonable limits;

e) development of seat-restraint systems capable of protecting the occupants from injurious dynamic forces, for all impacts inside the potentially survivable envelopes;

f) definition of human tolerance levels in 3-axial acceleration environments for given restraint systems.

All these tasks are essential, and particularly the importance and the difficulties of tasks "a" and "f" must not be underestimated.

A tremendous amount of work has been done on these topics, both in U.S. and in Europe, in the last 15 uears, and in fact crashworthiness of road and flight vehicles (particularly of helicopters) has improved sensibly; it is certain that this has already saved a significant number of lives.

But obviously further improvements are both desirable and possible. Moreover the increasing use of composite materials in the primary structures of flight vehicles poses new design problems, mainly connected with their relatively brittle behaviour. The energy absorbing capability of composite structures has been already demonstrated, but it is known that it requires a careful design of subcomponents; actually the energy absorbing mechanism of tough metal components relyes basically on inelastic buckling, while for composite components it must exploit progressive matrix cracking and fibre breaking.

The early crashworthiness researches were merely experimental; then the use of analytical models has been steadily increasing; a large variety of computer programs has been developed in U.S. and in Europe, and their progressive use and validation has largely changed the method of investigation. Today experiments are still essential, but they are no more adequate as the only research tool; they must be supported by, or better they must support analytical investigations, providing the values for model parameters and the final validation of analytical predictions methods.

This changes strongly the quality and the quantity of experiments; possibly the number of experiments can be reduced, because once the complete model has been validatet, it can be used several times in a large research without any further experiment. But the accuracy and the complexity of the experiments must increase, because many detail quantities must be accurately measured, and global behaviour is no longer sufficient.

2. ANALYTICAL MODELS

Analytical models are usually classified into hybrid and theoretical models, the main difference being the level of detail employed for the simulation of the actual structural and inertial characteristics.

In hybrid models, which may also be called Discrete Element models, the vehicle is represented by a relatively small number of lumped masses or rigid bodies, connected by massless non-linear structural elements, the latter simulating the structural behaviour of macroportions of the vehicle structure.

The characteristics of such macro-elements must be determined, possibly dynamically, by ad-hoc experiments, or by detailed Finite Element analysis, or by educated guess.

On the other hand theoretical models are detailed F.E. models, incorporating non-linear materials and large displacements, in principle capable of approximating very closely the detail behaviour of any structure, non requiring ad-hoc experiments to determine parameters.

Indeed the separation between hybrid (orD.E.) and theoretical (or F.E.) methods may not be so sharp. On one side hybrid models could be considered lumped mass/lumped siffness F.E. models, where often the coarseness of the mesh requires experimental measurements of inelastic stiffnesses; on the other side true F.E. programs are often used with relatively coarse models, requiring some element properties to be experimentally determined.

In fact the analytical models that have been developed and tested, and the relevant computer programs, cover a wide range of complexity and completeness , corresponding to a range of different purposes.

Figure 2 summarizes the main features that can characterize and classify the different codes.

The typical range of DOF used in F.E. codes is higher than the one for D.E. codes by more than one order of magnitude.

Integration schemes are both explicit and implicit. Explicit integration needs smaller memory occupation and computing time per step, but being only conditionally stable, requires very fine time steps. The most used explicit integration schemes are Predictor Corrector and Central Difference.
Implicit integration can be unconditionally stable, and thus it can employ larger time steps, having the effect of simply filterig out the higher frequencies, which often are not significant. But it needs larger memory and computer time per step, to assemble large sets of simultaneous equations.
Then explicit integration is more efficient for the most detailed models having a large number of DOF, particularly when the detail of the models requires a very fine time step, to track rapidly changing physical phenomena, as contacts, progressive yielding, breaking, etc.

In general explicit integration seems to be more efficient, and it is more generally used.

Another very important feature affecting strongly the flexibility and the completeness of the code, is the method employed to simulate contacts and contact forces.

The crudest mean to simulate contacts is the use of non-linear springs and contact elements. The great limitation of this method is that possible contacts and contact force directions must be known in advance, and only very limited sliding along the contact is allowed. But often possible contacts and rebounds can't be fixed in advance, and their search and simulation is one of the essential scopes of the analytical model. In this case contact surfaces must be geometrically defined, and the kinematics of their possible interference must be adequately analyzed. Once a contact is found, dynamical contact forces, and/or contact constraints must be generated.

In D.E. codes contact surfaces are some times defined as macro-surfaces, i.e. assemblies of geometrically simple surfaces, as cylinders, ellipsoids, toruses, cones or polyhedrons.

Non-elastic contact forces generally include rate dependent forces, friction forces, and plowing forces due to tangent motion of a hard surface plunging into a softer one, as e.g. in the case of a hard structural member plunging into a relatively soft ground.

In F.E. codes the contact surfaces are the outer element surfaces and the contacts are kinematically searched and established between the nodes of one part and the

surfaces of the other, and viceversa.

It must be realized that true contact simulation requires tremendous computing effort, because of the very large number of possible contacts that must be searched; contact processing may easily require more CPU time than structural analysis.

In D.E. models, failures can be simulated simply by the disappearence of massless structural elements, when a specified failure condition has been met. In F.E. models failures can be simulated by erosion modes, where failed elements are changed into free masses, or crack opening modes, where failure is simulated by the separation of adjacent elements, through the duplication of the connection nodes. Erosion modes are generally more suited for high-velocity impacts, while crack-opening modes are more suited for low-velocity impacts. In both cases new possible contact surfaces must be generated.

About the interaction with experiments, it is obvious that all analytical models require experimental validation; this would be essential but expensive, often difficult and sometimes impossible, as in the case of human biodynamical models.

Moreover hybrid models require subcomponent tests to determine dynamical crashing characteritics of macro-elements, while a detailed F.E. model needs experiments for determining material models. The latter can be a difficult task, as the development of an adequate rehological material model is both essential and very difficult, particularly for composite materials.

CPU times needed for a complete simulation may vary through some order of magnitude, from some tens of minutes for the simplest hybrid models, to 100 hours for the largest F.E. models. So the use of different complexities may require very different computer and man effort, and the choice of the optimal complexity for a certain simulation depends strongly from the purpose of the simulation itself.

3. EXAMPLES

In the following some well known codes and models are briefly mentioned and commented, just to outline the main features and differences. But this is far from being a complete list; many excellent codes and models are certainly missing.

KRASH

KRASH is one of the codes that has been more widely used in helicopter and aircraft crashworthiness studies.

KRASH has been developed at Lockheed California Company, originally under the auspices of U.S. Army, and subsequently under the sponsorship of the Federal Aviation Administration. It is a hybrid code, using explicit integration and non-linear springs to simulate contact forces.

Figures 3 and 4 show hybrid models analyzed with KRASH documented in the literature. The one in figure 3 is a complete helicopter model, and that in figure 4 is a helicopter composite cabin, including a simple seat-occupant model.

KRASH is considered a very valuable and very usable tool; good correlations have been found with experiments, many of them having been published.

VEDYAC

VEDYAC is a Discrete Element code developed at the University of Milano in cooperation and under the sponsorship of SWOV (Den Haag). It employs explicit integration and contact processor, the latter making use of the method of macro-surface interaction.

VEDYAC is currently used for automotive crash and crashworthiness studies; helicopter crash simulations are currently under development.
Figure 5 shows the model employed for a preliminary train-to-lorry collision; cylindrical macro-surfaces for contact computation are also shown in the figure. The interactions between train wheels and rails were also simulated through the contact processor, and this allowed to predict the derailement of the train bogies during the collision.

VEDYAC has been used also to handle antropomorphic dummy models, as in figure 6, relative to a car-to-pedestrian collision, or figure 7 showing a car colliding with a steel guardrail; for the latter simulation close correlation with experiments has been found.

The antropomorphic model shown in figures 6 and 7 corresponds roughly to the well known ATB model developed in U.S. by Calspan Corporation and MADYMO developed in the Nederlands by TNO (fig.8).

But it is generally felt that injury prediction in a multiaxial acceleration environment requires more detailed model; e.g. figure 9 shows detailed head-spine models developed by Belitshko and Privitzer for man (HSM) and baboon (BHSM). Once the

parameters of such models have been determined, and this may not be easy, these models can be very valuable analytical tools for human response and injury predictions. Their use requires an efficient D.E. code with contact processor.

DYCAST

DYCAST is a F.E. code developed by Grumman Aerospace Corporation under contract to NASA Langley Research Center. It has been largely used in helicopter crashworthiness studies, generally with moderate complexity models. It can employ both explicit and implicit integration schemes, and it can incorporate also hybrid elements, but it doesn't have a true contact processor.

Figure 10 shows a well known model that have been successfully used for helicopter cabin crash simulation; non-linear springs are employed as hybrid subfloor crushable elements, and to simulate contact with ground.

Figure 11 shows a DYCAST model for seat-occupant which gave very good correlation with dummy experiments.

CRASHMAS

CRASHMAS is a very powerful F.E. code developed recently by IABG (Ottobrun), from the previously developed DYSMAS code, the latter being a large software system, devoted to military applications, for the simulation of high velocity impacts and explosions.

CRASHMAS can handle very large F.E. models (typically 20.000 DOF), with very efficient computing techniques. It has an explicit integration scheme (Central Difference) and a true F.E. contact processor.

Figure 12 relative to the crash of an automotive front structure, shows clearly the effect of inter-element contacts in buckling; the lower picture, where contact processor has been used, shows a completely different deflection pattern.

Figure 13 shows the collision of a missile against a deformable target plane, made with DYSMAS/L, where the high level of detail is clearly visible.

CRASHMAS gave excellent correlations with experiments, even in details, and its use is considered with increasing interest by car industries in FRG, particularly for its ability to allow detailed simulations prior to any experimental test.

4. CONCLUSIONS

Analytical models so far developed and tested by different Institutions and Companies in the world cover a wide range of complexity, completeness and computational effort. All of them have been found useful and gave good correlation with experiments.

Then the question "what is the best complexity for a crash simulation?" doesn't have a unique answer.

Certainly the relatively simple hybrid models are much easier to use, and can give very valuable results, provided a certain modeling "art" is acquired by the user through intelligent experience.They may be very useful, particularly when the same model must be employed for several computations, to study the trends with variation of encroachement conditions or other parameters.

It is rather obvious that when a F.E. code is used with moderate number of DOF (less than 1000) the difference in use with hybrid codes tends to vanish.

On the other hand the most complex and complete F.E. models are very attracting, particularly for their ability to simulate realistically structural detail behaviour, reducing the amount of the experiments required, and improving the quality of the information obtainable.

In the future the introduction of new generation large computers and the relevant software improvements will possibly make the use of such large F.E. models more and more attractive and usable.

In any case it must be observed that also large F.E. modeling requires experience and some "art".

Moreover the importance of biomechanical models for human response and injury prediction must not be understimated, if the science of crashworthiness must progress harmonically.

It must be observed that the biomechanical models so far developed are at most human response models; if they have to become injury prediction models they need correlations between element dynamics (i.e. relative displacements and angles, accelerations, forces, etc.) and injuries.

Possibly in the future the use of detailed non-linear Finite Element models could give important contributions also to this essential problem.

Finally international co-operation will be very beneficial and should be promoted in the very essential field of crashworthiness.

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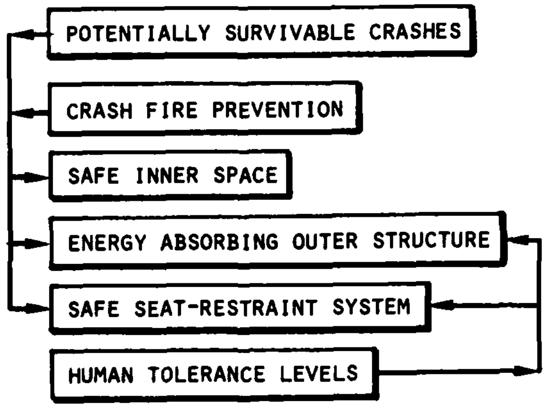


Figure 1. Crashworthiness issues

	DISCRETE EL. MODELS	FINITE EL. MODELS
No. of DOF	100 - 1000	1000 - 20000
Integration scheme	Explicit: KRASH, VEDYAC, HSM Implicit: ATB, MADYMO	Explicit: DYCAST Implicit: DYCAST, CRASHMAS HEMP/ESI, DYSMAS/L
Contact simulation	Macrosurface interf.: VEDYAC, ATB, MADYMO, HSM Non-linear spring: KRASH	FE Contact Processor: CRASHMAS, DYSMAS/L, HEMP/ESI Non-linear spring: DYCAST
Failure modes	Disappearance of structural connections VEDYAC	Erosion mode: DYSMAS/L HEMP/ESI Crack opening mode: CRASHMAS, DYSMAS/L
Experiments required	Macroelements properties Validation	Material properties Validation
Main purposes	Parametric investigations Biomechanical models	Detail analyses of structures and subcomponents

Figure 2. Main features of mathematical models

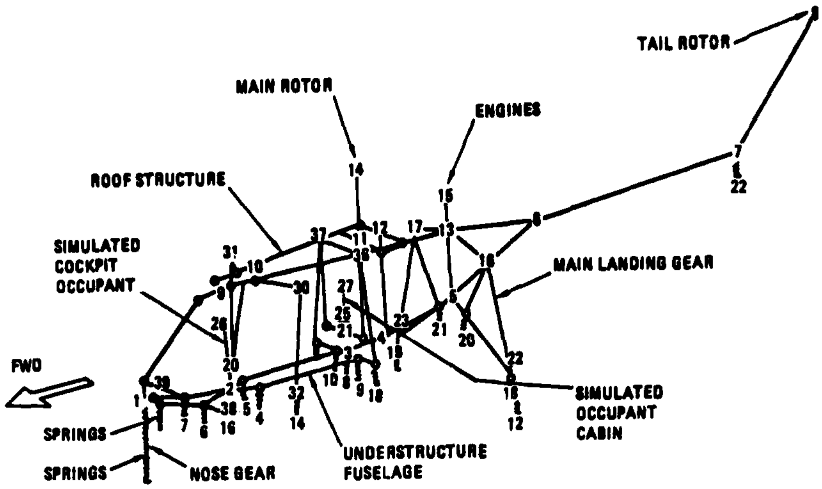


Figure 3. Helicopter model (KRASH, from 5)

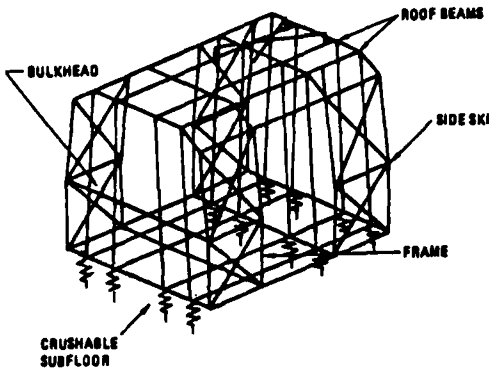


Figure 4. Helicopter cabin model (KRASH, from 4)

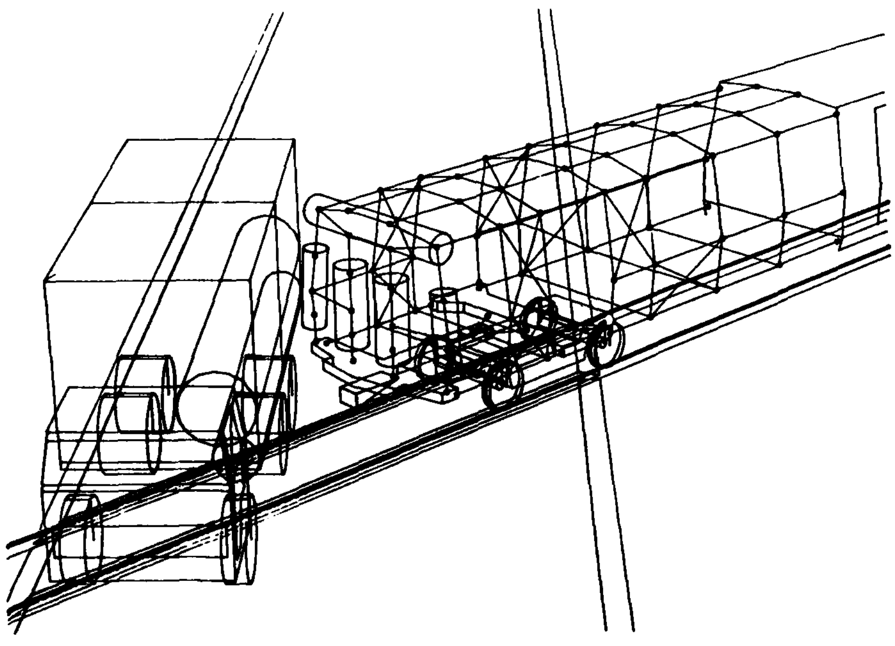


Figure 5. Train to lorry collision model (VEDYAC)

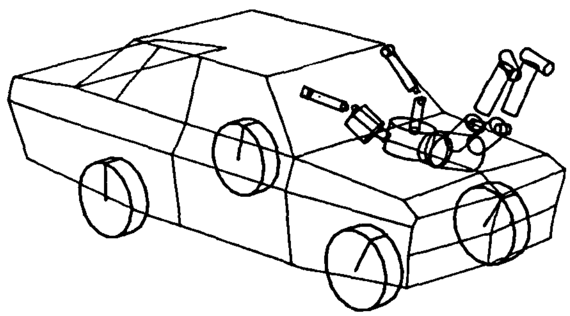


Figure 6. Car to pedestrian collision (VEDYAC)

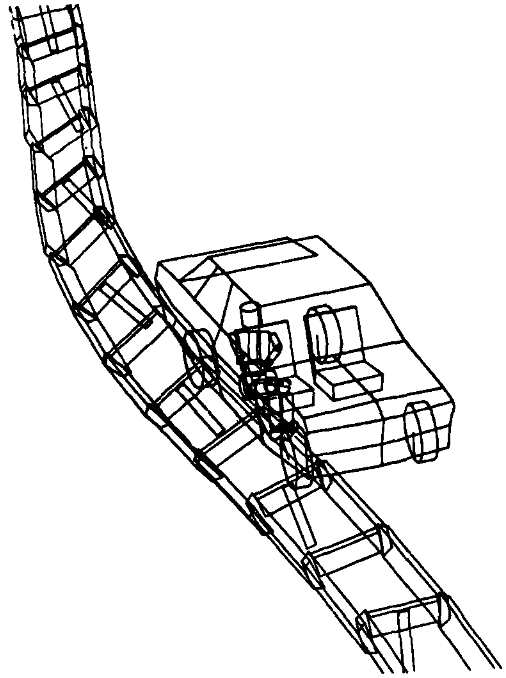


Figure 7. Collision of a car with a passenger against a steel guard rail (VEDYAC)

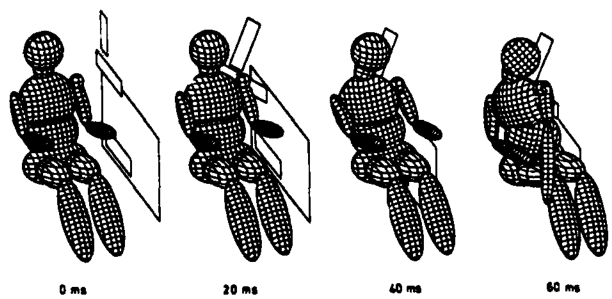


Figure 8. Simulation of a car passenger during a lateral collision (MADYMO, from 24)

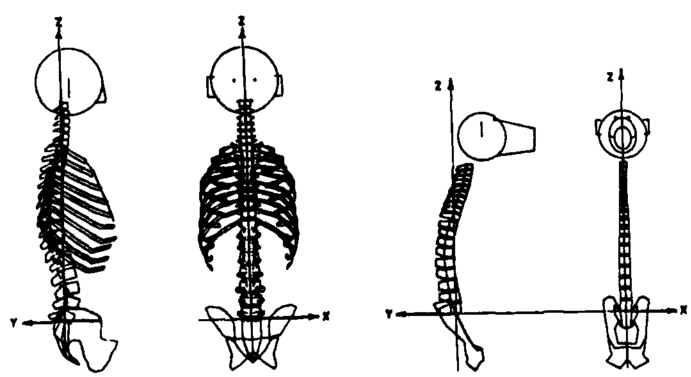
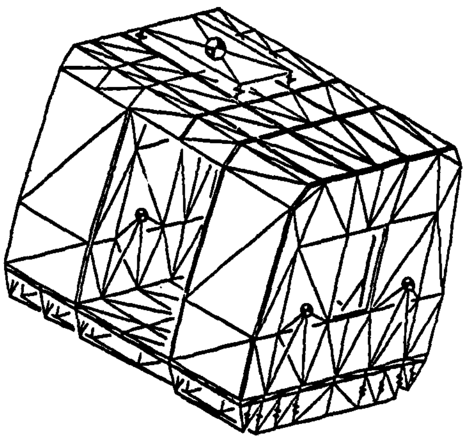
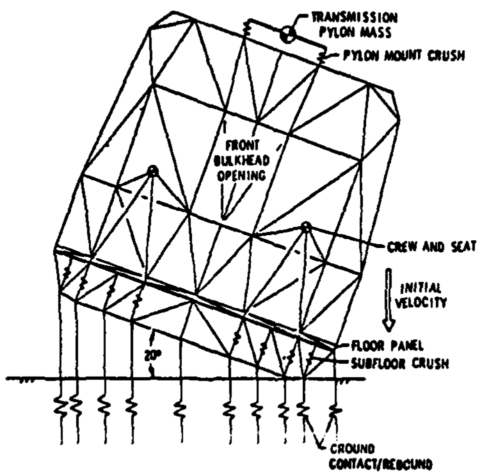


Figure 9. Head-Spine models: man (left) and baboon (right) (from25)



Helicopter cabin structure, model overall view



Helicopter cabin structure model, front view

Figure 10. Helicopter cabin model (DYCAST, from 10)

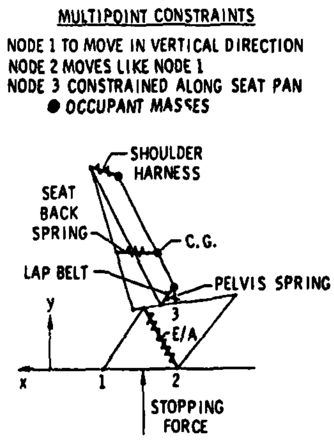


Figure 11. Seat-occupant model (DYCAST, from 8)

Without Contact Processor:

With Contact Processor:

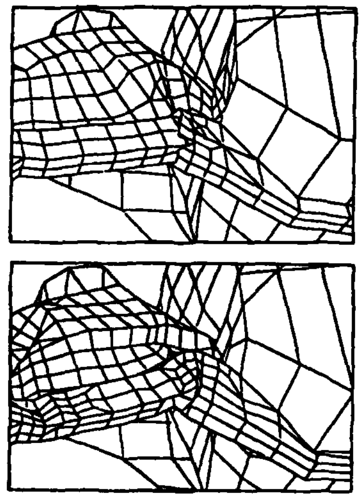


Figure 12. Effect of a true FE contact processor (CRASHMAS)

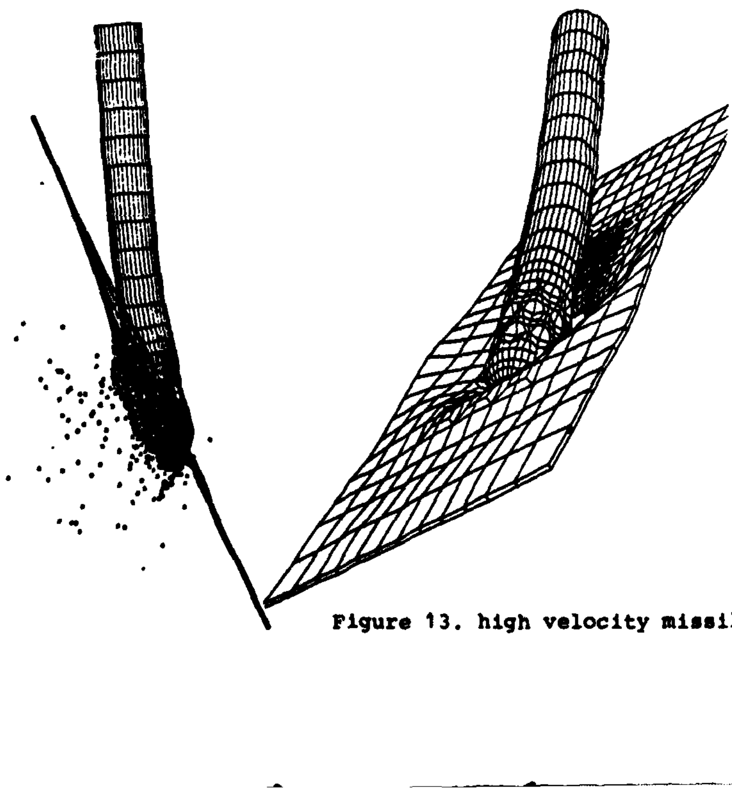


Figure 13. high velocity missile impact (DYSMAS/L)

REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's Reference	3. Further Reference	4. Security Classification of Document
	AGARD-R-737	ISBN 92-835-1525-0	UNCLASSIFIED

5. Originator	Advisory Group for Aerospace Research and Development North Atlantic Treaty Organization 7 rue Ancelle, 92200 Neuilly sur Seine, France
6. Title	CRASHWORTHINESS OF AIRFRAMES
7. Presented at	the 61st Meeting of the Structures and Materials Panel of AGARD in Oberammergau, Germany, 8—13 September 1985.

8. Author(s)/Editor(s)	9. Date
Various	April 1986

10. Author's/Editor's Address	11. Pages
Various	38

12. Distribution Statement	This document is distributed in accordance with AGARD policies and regulations, which are outlined on the Outside Back Covers of all AGARD publications.

13. Keywords/Descriptors

Airframes
Impact strength
Damage
Structural analysis

14. Abstract

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AGARD Report No.737
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CRASHWORTHINESS OF AIRFRAMES
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